

Searches for Physics Beyond the Standard Model at Colliders

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Abstract. All experimental measurements of particle physics today are beautifully described by the Standard Model. However, there are good reasons to believe that new physics may be just around the corner at the TeV energy scale. This energy range is currently probed by the Tevatron and HERA accelerators and selected results of searches for physics beyond the Standard Model are presented here. No signals for new physics have been found and limits are placed on the allowed parameter space for a variety of different particles.

1. Introduction

Despite the amazing success of the Standard Model (SM) there are strong theoretical motivations for the existence of new particles could be produced at TeV scale colliders today or in the very near future. Many new hypothetical particles have been suggested as a result of a variety of theoretical models that try to solve the Standard Model's problems of extrapolating to high energies near the Planck scale. In this article the recent searches for many different kinds of particles are presented: supersymmetric partners of the SM particles, new gauge bosons, extra spatial dimensions and compositeness. The colliders that presented new results probing the existence of new particles via direct production are the currently operating Tevatron and the very recently closed HERA colliders.

2. The Tevatron $p\bar{p}$ and the HERA $e^\pm p$ Colliders

At the Tevatron in the US near Chicago protons are collided with anti-protons with a center-of-mass energy of $\sqrt{s} = 1.96$ TeV. The "Run II" period of the Tevatron is in progress since 2001 and by now about 2 fb^{-1} of integrated luminosity have been accumulated by the CDF and D0 experiments. The Tevatron is currently the highest energy collider world-wide until the startup of the Large Hadron Collider (LHC) in Summer 2008.

The HERA $e^\pm p$ collider has operated for fifteen years, between 1992 and June 2007. While its primary achievement has been its amazing measurements of the proton structure functions, in particular at low x , the H1 and ZEUS experiments have also performed many searches for new particles some of which will be covered in this article. The total integrated luminosity of H1 and ZEUS is about 0.5 fb^{-1} .

3. Supersymmetry

Supersymmetry [1] (SUSY) is by far the most popular theory that extends the Standard Model since it provides a natural solutions to the hierarchy problem [2, 3, 4] and the unification of gauge forces [5] and an excellent candidate for the cold dark matter [6, 7] in the Universe.

SUSY predicts a partner for each SM particle that carries the same quantum numbers but differs by half a unit of spin. The lightest SUSY particle (LSP) could be stable if a quantum number called R -parity (R_p) is conserved. The primary candidate is currently the lightest neutralino and this is also an excellent candidate for the Cold Dark Matter. Alternative models suggest the LSP to be the gravitino and these are also discussed here. SUSY particles then typically cascade decay through SM particles to the LSP which escapes detection (if R_p is conserved).

3.1. Generic Squarks and Gluinos

At the Tevatron one of the primary targets of SUSY searches are the colored particles, squarks and gluinos, that are rather copiously produced at hadron colliders. In this search the signature is multi-jet production (from the quarks from the squark or gluino decay) and large missing transverse energy (due to the neutralinos). This search has been made by both the CDF and D0 collaborations: in both cases the experimental collaborations have searched in the 2-jet+ \cancel{E}_T , the 3-jet+ \cancel{E}_T and the 4-jet+ \cancel{E}_T signatures which are more or less dominant depending on the relationship between the gluino and squark mass. If $m(\tilde{g}) \ll m(\tilde{q})$ the dominant process is gluino-pair production resulting in a 4-jet final state. If $m(\tilde{g}) \gg m(\tilde{q})$ the process is dominated by squark pair production, yielding a final state of 2 jets and \cancel{E}_T . As an example the \cancel{E}_T distribution for the 3-jet final state which is dominant if $m(\tilde{g}) \approx m(\tilde{q})$ is shown in Fig. 1 for CDF. The dominant SM backgrounds arise from W +jets, Z +jets and $t\bar{t}$ production, and a difficult further background arises from QCD multi-jet production where \cancel{E}_T arises due to severe mismeasurements of the jets.

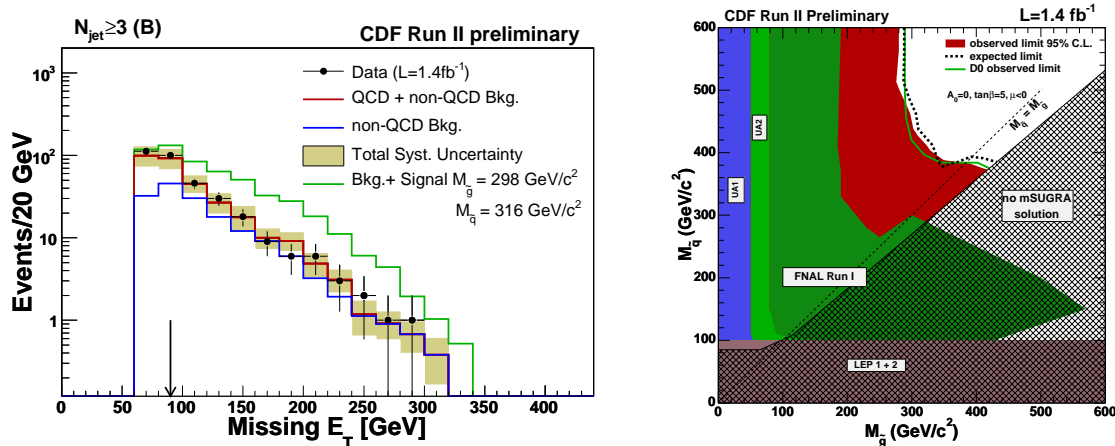


Figure 1. Left: The \cancel{E}_T distribution for the 3-jet final state in the squark/gluino search of CDF. Right: The exclusion limits at 95% CL in the plane of gluino and squark mass: shown are the limits from UA1, UA2, LEP, Run I of the Tevatron and Run II CDF and D0.

Both CDF and D0 have performed this search [8] using 1.4 and 1.0 fb^{-1} , respectively, and neither experiment found any excess indicating the presence of squarks or gluinos. Thus both experiments set lower limits on the masses of these particles as seen in Fig. 1: the gluino is constrained to be heavier than $290 \text{ GeV}/c^2$ at 95% CL.

3.2. *Sbottom and Stop Quarks*

For the above search interpretation the SUSY partners of the 3rd generation quarks were not considered since they would introduce a undesired model dependence and targeted searches are designed for these. The stop quark is particularly critical in supersymmetry as it is the one that cancels the large radiative corrections to the Higgs mass from the top quark. Due to the large mass of the SM top quark the stop quark mass splitting is large, and one of the two mass eigenstates is expected to be the lightest of all squarks:

$$m_{\tilde{t}_{1,2}}^2 = \frac{1}{2}(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 \mp \frac{1}{2}\sqrt{(m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2)^2 + 4m_t^2(A_t - \mu \tan \beta)^2})$$

The Tevatron is most sensitive to the direct pair production, $p\bar{p} \rightarrow \tilde{t}\tilde{t}^* + X$ and many different decay topologies are possible depending on the masses of the \tilde{t} and the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$. If $m(\tilde{t}) > m(\tilde{\chi}_1^0) + m(t)$ the decay will proceed through $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ but the Tevatron experiments are not yet sensitive to this case since the cross section in this mass range are too low. If $m(\tilde{\chi}_1^\pm) + m(b) < m(\tilde{t}) < m(\tilde{\chi}_1^0) + m(t)$ the decay proceeds via $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow b\ell\nu\tilde{\chi}_1^0$ and if this decay is also forbidden kinematically it goes via $\tilde{t} \rightarrow c\tilde{\chi}_1^0$. These last two decay modes have both been searched for (see Ref. [9, 10, 11] and the most recent search [12] in the $\tilde{t} \rightarrow c\tilde{\chi}_1^0$ mode by the D0 collaboration is shown here. Fig. 2 shows the \cancel{E}_T distribution for events with two charm-tagged jets and a variety of other cuts that are designed to reduce the instrumental background from multi-jet production and backgrounds from W/Z +jets and $t\bar{t}$ production (for details see. Ref. [11]). The data agree with the SM prediction and limits are placed in the plane of $m(\tilde{t})$ versus $m(\tilde{\chi}_1^0)$. For e.g. $m(\tilde{\chi}_1^0) = 63 \text{ GeV}/c^2$ the limit on the stop mass is $> 149 \text{ GeV}/c^2$.

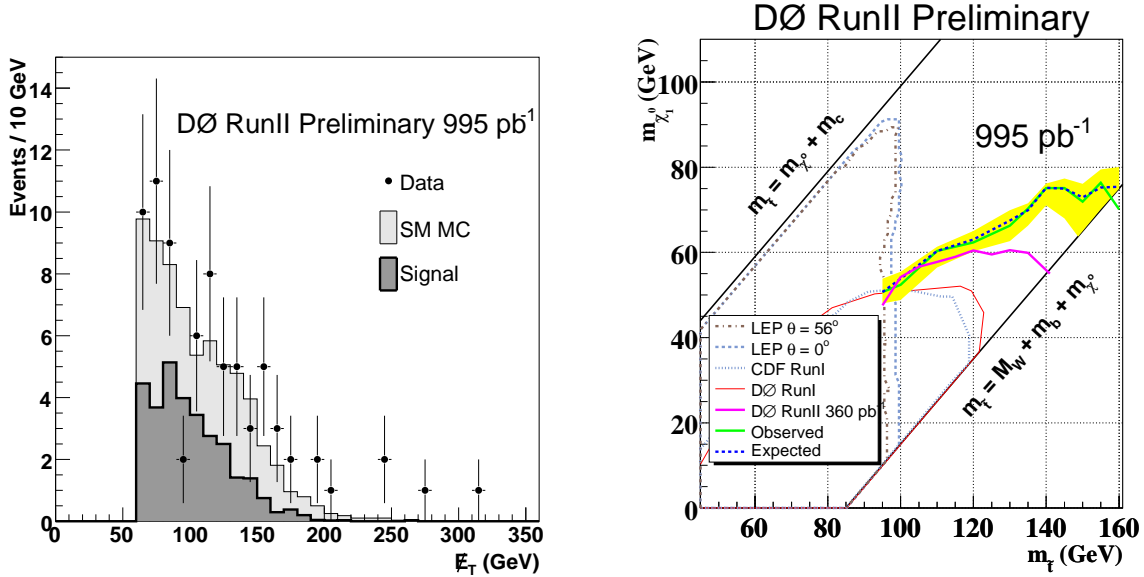


Figure 2. Left: The \cancel{E}_T distribution for $pp \rightarrow \tilde{t}\tilde{t}^* + X \rightarrow cc\tilde{\chi}_1^0\tilde{\chi}_1^0 + X$ search of D0. Right: $m(\tilde{t})$ vs $m(\tilde{\chi}_1^0)$ is shown. Displayed are the kinematic boundaries of this search and the exclusion limits from CDF, D0 and the LEP experiments. the yellow band in the D0 analysis shows the uncertainty due to theoretical uncertainties on the cross section predictions.

3.3. *Charginos and Neutralinos*

Another class of interesting searches are the searches for direct production of charginos and neutralinos. Within models where the LSP is the lightest neutralino a promising search

strategy is the production of three leptons and large \cancel{E}_T . In gauge mediated SUSY breaking (GMSB) [13, 14] type models where the LSP is the gravitino the signature of $\gamma\gamma + \cancel{E}_T$ has been explored.

The trilepton search is unfortunately relatively model-dependent since the acceptance largely depends on the lepton flavor (in particular on the τ admixture) and the kinematic properties of the leptons, in particular their transverse momentum. The searches are divided into many sub-signatures to obtain maximum sensitivity. An example of the \cancel{E}_T distribution in one of the search signatures is shown in Fig. 3. Neither CDF nor D0 observes any significant excess above the SM expectation [15, 16] and limits are placed on the cross section times branching ratio versus chargino mass. The limits are about 0.1-0.2 pb and constrain the chargino mass in specific model up to 144 GeV/ c^2 .

The class of GMSB models where the next-to-lightest SUSY particle (NLSP) is the $\tilde{\chi}_1^0$ and that decays to $\tilde{G} + \gamma$ is experimentally relatively easy to observe as there are no intrinsic SM backgrounds that give the same signature. D0 has searched for this signature using 1 fb $^{-1}$ of data and find 4 events with $\cancel{E}_T > 60$ GeV compared to 1.5 ± 0.4 expected from backgrounds. The full \cancel{E}_T spectrum is shown in Fig. 3. A lower limit on the chargino mass of 231 GeV is placed.

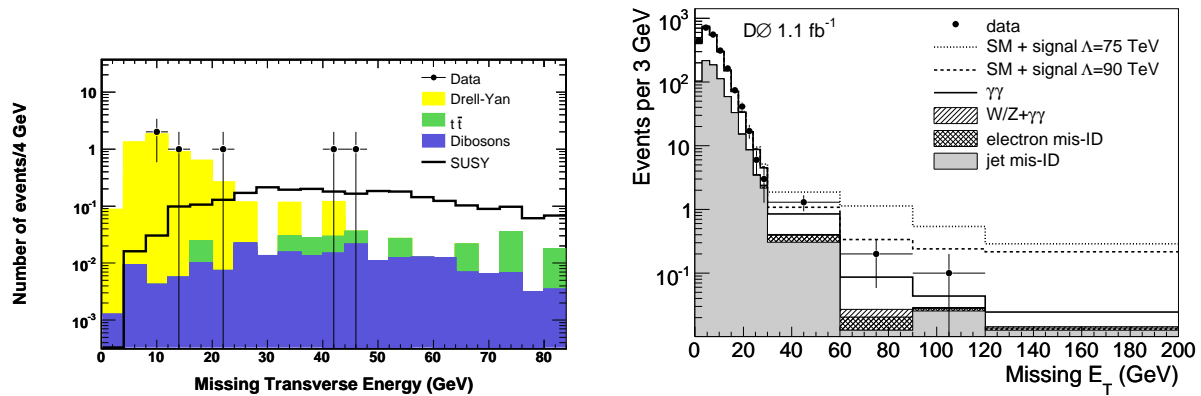


Figure 3. Left: The \cancel{E}_T distribution for the CDF trilepton search $p\bar{p} \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm + X \rightarrow 3\ell \tilde{\chi}_1^0 \tilde{\chi}_1^0 + X$. This example show the search for two electrons and an isolated charged track. Right: The \cancel{E}_T distribution for diphoton events as observed by D0. In both figures the data (markers) and the backgrounds contributions (histograms) are shown. Also shown are example signal distributions.

3.4. Long-lived Particles

Recently a special interest has developed in searches for long-lived particles, i.e. particles that live for a while before they decay (see Ref [17] for a review). These lead to distinct experimental signatures depending on their lifetime and their exact properties:

- they can traverse the full detector without stopping. The experimental signature is a slow charged particle that is tracked through the tracking detector and triggered in the muon system. Depending on whether they are strongly or weakly produced they can undergo charge transformations within the detector. For strongly interacting particles this transformation leads to an effective suppression by a factor 4 per particle. This signature is e.g. produced by gluinos that can be very long-lived in split-SUSY [18] or stable $\tilde{\tau}$ -leptons in GMSB type models [19].

- they can get stuck in the calorimeter and decay there at a later time. The experimental signature here is a large energy deposition out of time with any collision. This signature is also predicted by gluinos in split-SUSY and called “stopped gluinos”.
- they can travel for a bit but still decay inside the tracking volume before the calorimeter if the lifetime is of the order of about 10 ns. This is predicted e.g. in GMSB models where the lightest neutralino could have a lifetime and thus travel a significant amount of time before it decays to a photon and a gravitino.

CDF and D0 searched for slow particles traversing the full detector, and both trigger the particle by a signal in the muon system. CDF uses the time-of-flight detector just outside the tracking system at a radius of about 1m to measure the arrival time with a resolution of 100 ps and reconstructs the mass by $m = p\sqrt{1/\beta^2 - 1}$. D0 uses the timing from the muon system itself. For weakly interacting particles CDF observes no evidence of such particles and places cross section limits for particles with $p_T > 40$ GeV, $|\eta| < 1$ and $0.4 < \beta < 0.9$ of 10 fb, for strongly interacting particles the corresponding limit is 48 fb [20]. The mass distribution is shown in Fig. 4. As an example this constrains a stable stop quark to have a mass greater than 250 GeV/ c^2 . D0 has carried out a similar search [20].

D0 have also searched for so-called “stopped gluinos” by looking for events where no interaction is seen but there is a large energy deposit in the calorimeter [21]. The main backgrounds are cosmic ray and beam halo muons that shower in the calorimeter. Fig. 4 shows the data compared to the SM expectation and a hypothetical signal. Since there is no sign of any deviation from the SM limits are placed depending on the assumed lifetime. These are shown in Fig. 4 and compared to the predicted cross section. The analysis probes gluino masses between 175 and 320 GeV depending on the details of the model.

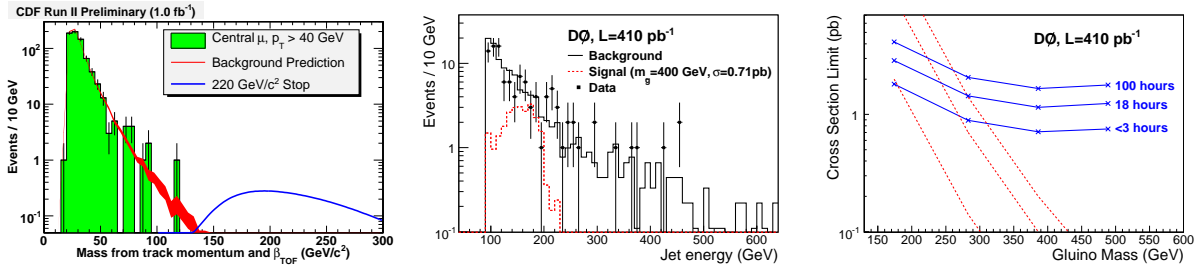


Figure 4. Left: Mass distribution for the CDF search for a long-lived charged particle traversing the detector. Middle: Jet energy distribution for D0’s search for a long-lived particle that later decays in the detector out of time with any collision. Right: Cross section time branching ratio for stopping gluinos. Theoretical predictions (red dashed lines) and experimental upper limits (blue solid lines) are shown for different assumptions.

CDF has also searched for photons that arrive out of time, so-called “delayed photons” [22] which can stem from a long-lived massive particle. CDF measures the arrival time of the photon in the electromagnetic calorimeter. The data show no sign of any excess and are used to constrain the neutralino mass to be larger than 101 GeV/ c^2 for a lifetime $\tau_{\tilde{\chi}_1^0} = 5$ ns.

3.5. Higgs boson

Within the minimal supersymmetric Standard Model (MSSM) there are two scalar fields resulting in a total of five physical Higgs bosons: the scalar h and H , the pseudo-scalar A and the two charged states H^\pm . At high $\tan\beta$ the A is degenerate with either the h or the H

or with both and additionally the cross section is enhanced [23, 24, 25] with $\tan^2 \beta$:

$$\sigma = 2\sigma_{SM} \frac{\tan^2 \beta}{(1 + \Delta_b)^2} \frac{9}{[9 + (1 + \Delta_b)^2]}$$

At high $\tan \beta$ the Higgs boson decays about 90% to $b\bar{b}$ and 10% to $\tau^+\tau^-$. The searches presented here use the $\tau^+\tau^-$ decay modes. The signal is selected by requiring at least one electron or muon from one of the tau decays (τ_e, τ_μ) and then the other tau can either decay hadronically (τ_h) or also leptonically. Due to the outgoing neutrinos it is not possible to fully reconstruct the invariant mass of the two τ 's in this inclusive search. Thus a quantity called “visible” mass is defined as $m_{vis} = p_T(\tau, 1) + p_T(\tau, 2) + \cancel{E}_T$. This is shown for the CDF and D0 searches in Fig. 5 and Fig. 6. While CDF observed a small excess at $m_A \approx 160$ GeV a slight deficit is seen by D0. The experiments are sensitive to $\tan \beta \approx 40 - 60$ for $m_A < 200$ GeV as seen in Fig. 6.

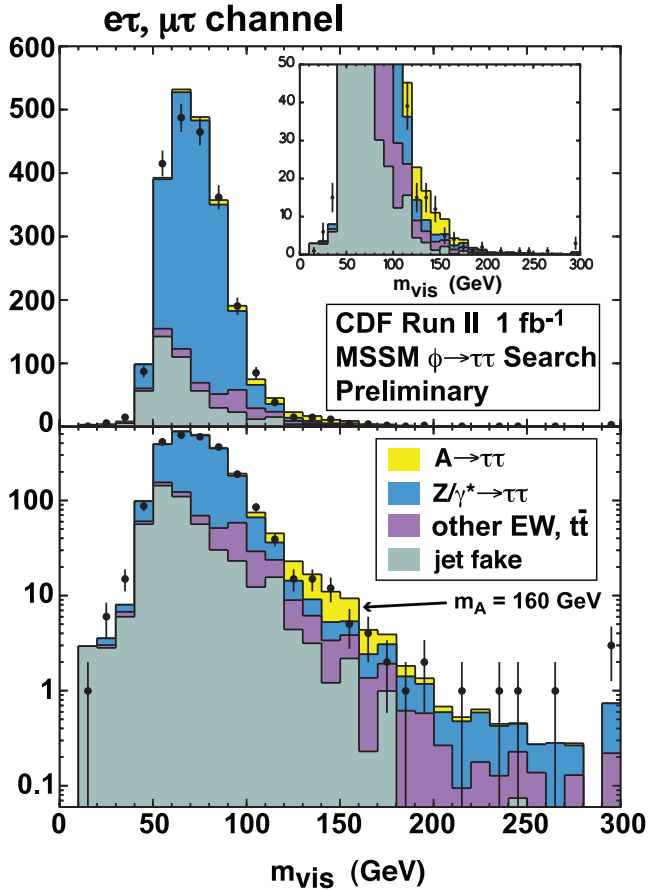


Figure 5. CDF’s m_{vis} distribution for the MSSM Higgs search in the di-tau decay mode ($\phi \rightarrow \tau^+\tau^-$ with $\phi = A, h, H$).

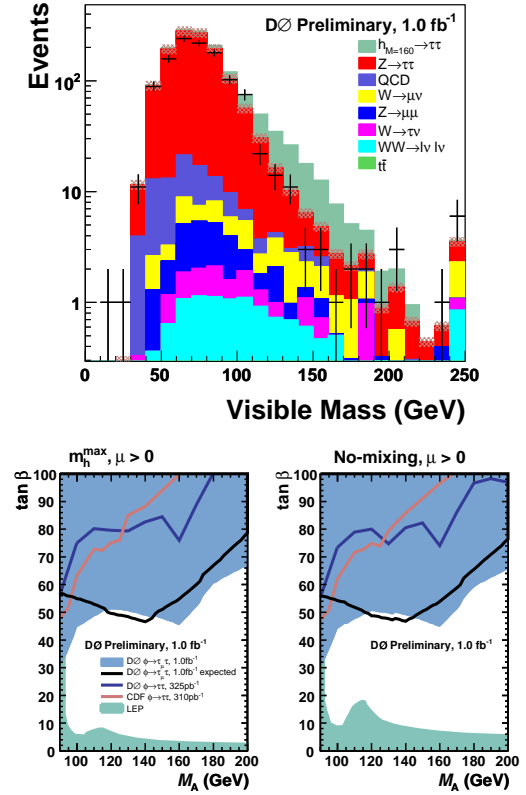


Figure 6. Top: D0’s m_{vis} distribution for the MSSM Higgs search in the di-tau decay mode ($\phi \rightarrow \tau^+\tau^-$ with $\phi = A, h, H$). Bottom: Plane of $\tan \beta$ versus m_A : the excluded regions is in light blue. Also shown are previous results and the expected limit. The limits are shown in a specific scenario called “no-mixing” [26]

Alternative searches probing the MSSM Higgs boson at high $\tan \beta$ are those for multi- b -jet

production which have also been carried out by CDF and D0 [27] but also show no sign of new physics.

Similar parameter space is probed indirectly in rare B -decays (e.g. $B_s \rightarrow \mu^+\mu^-$ by CDF/D0 [28] and $B^+ \rightarrow \tau^+\nu_\tau$ by Belle/Babar [29]), in τ decays (e.g. $\tau \rightarrow \mu\eta$ by Belle/Babar [30, 31]) and in rare kaon decays (e.g. in the precision measurement of $R_K = \Gamma(K \rightarrow \mu\nu)/\Gamma(K \rightarrow e\nu)$ by KLOE and NA48 [32, 33]).

4. Beyond Supersymmetry

Even though Supersymmetry is the most favored model of physics beyond the SM, there is of course a good chance that it does not represent Nature and that other particles appear at the TeV scale.

4.1. Contact Interactions and Compositeness

A classic way of parameterizing new physics is the introduction of contact terms that mediate 4-fermion interactions, similar to Fermi's proposal for explaining β -decay where the contact term was later explained by the exchange of a W^\pm boson. The Lagrangian for a contact interaction can most generally be written as

$$\mathcal{L} = \frac{4\pi}{\Lambda^2} \sum_{i,j} \eta_{ij} q_i \gamma^\mu \bar{q}_i \ell_j \gamma_\mu \bar{\ell}_j$$

where η_{ij} is a sign factor that is positive (negative) for constructive (destructive) interference and $i, j = L, R$ denote left and right-handed helicities of the quarks and leptons.

Figure 7 shows inclusive spectra of the dijet cross section versus the dijet invariant mass at the Tevatron and the Neutral and Charged Current cross sections at HERA. A beautiful agreement between the data and the Standard Model predictions is observed over up to seven orders of magnitude.

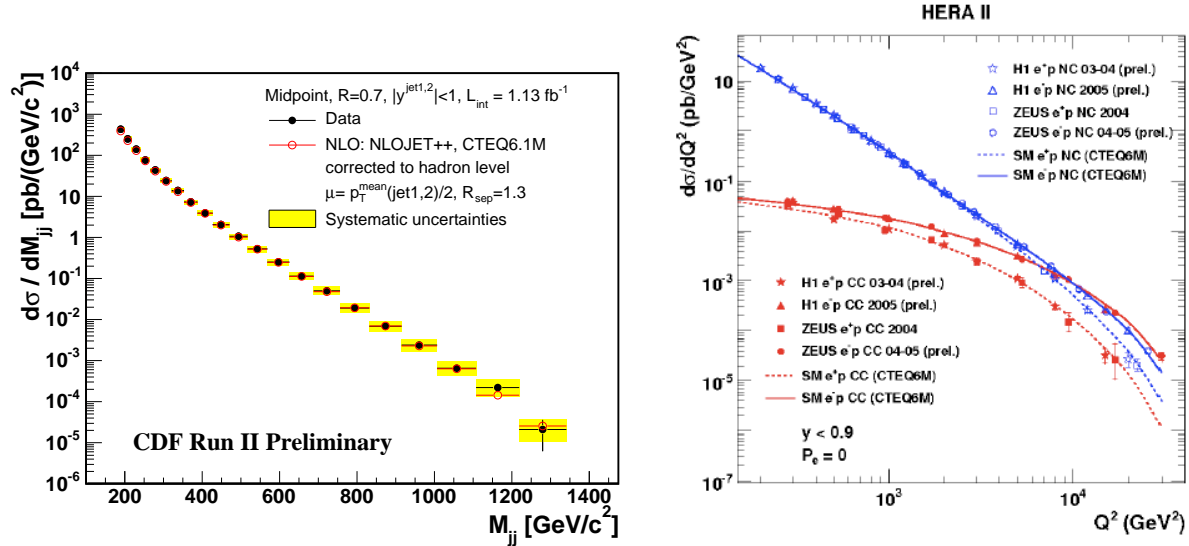


Figure 7. Left: The dijet cross section versus the dijet invariant mass, M_{jj} . Right: The neutral and charged current cross section versus Q^2 for e^+p and e^-p scattering.

These can be used to constrain contact interactions and e.g. for $eeqq$ contact terms some example constraints from D0 and ZEUS are given in table 1.

Table 1. Limits on $eeqq$ contact interactions terms from the D0 and ZEUS collaborations and limits on $\mu\mu qq$ contact terms from D0. All limits are given in units of TeV.

Model	Coupling Structure					
	ZEUS $eeqq$		D0 $eeqq$		D0 $\mu\mu qq$	
	Λ^-	Λ^+	Λ^-	Λ^+	Λ^-	Λ^+
LL	4.2	4.2	6.2	3.6	7.0	4.2
LR	2.0	3.6	4.8	4.5	5.1	5.3
RL	2.3	3.6	5.0	4.3	5.2	5.3
RR	4.0	3.8	5.8	3.8	6.7	4.2

Difermion mass spectra are also sensitive to many specific models, e.g. in models with large extra dimensions at the TeV scale (ADD [34]) or models where one of the extra dimensions is warped (RS [35]) or models predicting new gauge bosons (Z' , W').

Figure 8 shows the inclusive dielectron, diphoton and the $t\bar{t}$ mass spectra that are sensitive to new electrically neutral resonances. Using these data a Z' with SM couplings is constrained to be heavier than $925 \text{ GeV}/c^2$ by CDF [36], and a RS-Graviton $> 900 \text{ GeV}/c^2$ for $k/M_{Pl} = 0.1$ (and $> 300 \text{ GeV}/c^2$ for $k/M_{Pl} = 0.01$ (see CDF [36] and D0 [37]). A Z' -boson in topcolor models is constrained to be heavier than $720 \text{ GeV}/c^2$.

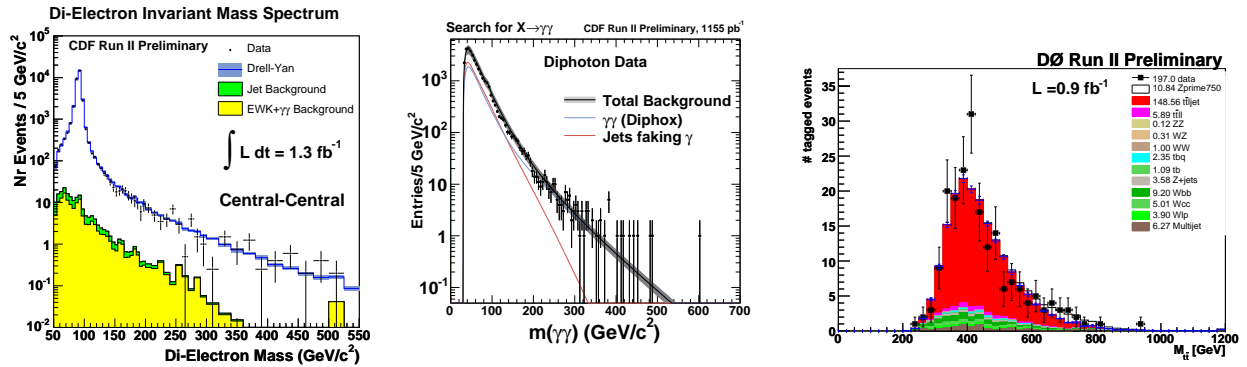


Figure 8. Invariant ee (left) and $\gamma\gamma$ (middle) mass spectrum at CDF, and the $t\bar{t}$ invariant mass spectrum by D0. In all cases the data (points) are compared to the SM expectation (histograms).

Figure 9 shows the transverse mass for $p\bar{p} \rightarrow e\nu_e + X$ events and the reconstructed mass for $p\bar{p} \rightarrow t\bar{t} + X$ events. Both signatures are sensitive to e.g. W' production and have been used to constrain a W' to have $m(W') > 965 \text{ GeV}/c^2$ (using the D0 $e\nu_e$ analysis) and $m(W') > 760 \text{ GeV}/c^2$ using the CDF $t\bar{t}$ analysis). Note, that while the $e\nu_e$ only probes left-handed currents the $t\bar{t}$ analysis is sensitive to both left- and right-handed currents.

Compositeness models also predict excited states of the familiar fermions denoted e.g. e^* , ν^* , q^* etc. These decay to a gauge boson and a SM fermion. Searches for these particles have been carried out at both Tevatron and HERA. Example spectra for the search $\nu^* \rightarrow W e \rightarrow j j e$ from H1 and $e^* \rightarrow e \gamma$ from D0 are shown in Figure 10. In all cases the data are not showing any sign for an excess consistent with excited fermion production. A summary of the limits placed on the mass and coupling of excited electrons is shown in Figure 10. There is a nice competition between the LEP, the Tevatron and the HERA experiments which all exclude different and complementary regions of the parameter space.

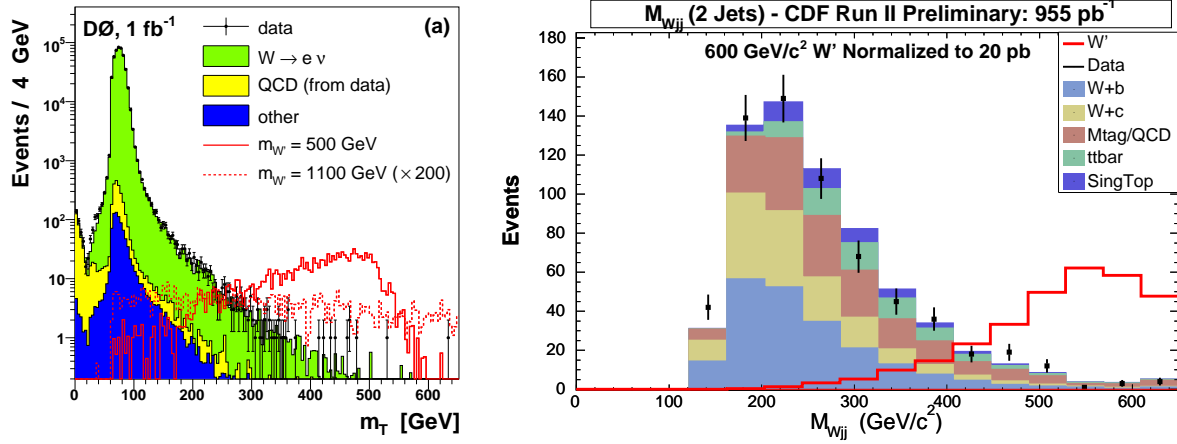


Figure 9. Left: Transverse $e\nu_e$ mass in D0's W' search. Right: Invariant mass of tb in CDF's W' search. In both cases the data (points) are compared to the SM predictions (filled histograms). Example W' signals are also shown as open histograms.

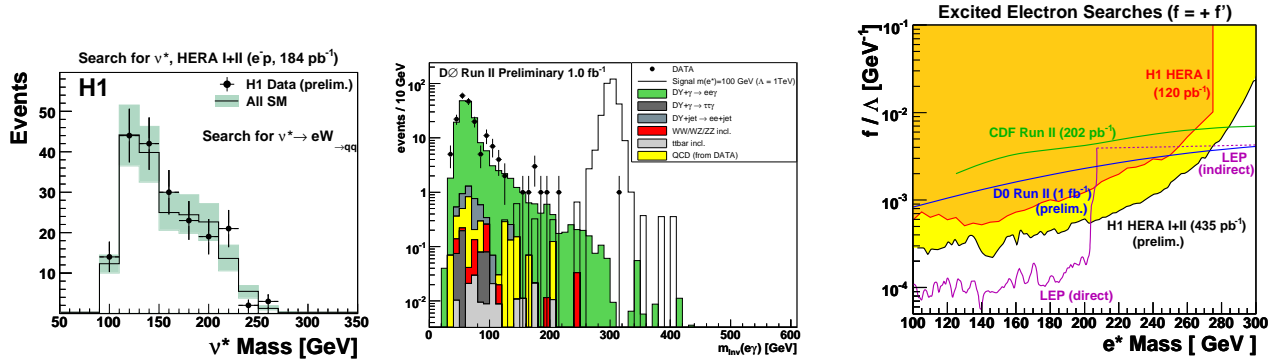


Figure 10. Left: Invariant ejj mass in the H1 search for $\nu^* \rightarrow ejj$. Middle: Invariant $e\gamma$ mass in the $e^* \rightarrow e\gamma$ search at D0. Right: Exclusion limits in the plane of coupling (f/Λ) and e^* mass. The shaded areas and the areas above the lines are excluded.

5. Conclusions and Outlook

The current collider experiments continue to vigorously search for new particles as predicted by many theories beyond the Standard Model, but so far the data show excellent agreement with the SM expectations in all experimental signatures. Thus the experiments are placing tighter and tighter limits on the mass range allowed for these particles, e.g. in SUSY, Extra Dimension and compositeness models.

There is still more data to come and to be analyzed at the Tevatron and HERA and we look forward to many more results in the next few years. In Summer 2008 the Large Hadron Collider will also start to enter the scene and may finally observe the long-sought new physics at the Tera-scale.

Acknowledgments

I wish to thank the organizers of this conference for the excellent preparation and the interesting and stimulating conference programme.

References

- [1] Wess J and Zumino B 1974 *Nucl. Phys. B* **70** 39
- [2] Witten E., 1981 *Nucl. Phys. B* **188** 513
- [3] Sakai N, 1981 *Z. Phys. C* **11** 153
- [4] Dimopoulos S 1981 *Nucl. Phys. B* **193** 150
- [5] Dimopoulos S, Raby A and Wilczek F 1981 *Phys. Rev. D* **24** 1681
- [6] Ellis J, Hagelin J S, Nanopoulos D V, Olive K and Srednicki M 1984 *Nucl. Phys. B* **238** 453
- [7] Goldberg H 1982 *Phys. Rev. Lett* **50** 1419
- [8] Portell X (for the CDF and D0 Collaborations), *in these proceedings*
- [9] Abazov V M *et al.* (D0 collaboration) submitted to *Phys. Lett. B* arXiv:07072846
- [10] Aaltonen T *et al.* (CDF collaboration) 2007, *Phys. Rev. D* **76** 072010
- [11] Abazov V M *et al* (D0 Collaboration) 2007 *Phys. Lett. B* **645** 119;
- [12] Biscarat C (for the CDF and D0 Collaborations), *in these proceedings*
- [13] Dine M *et al.* 1996 *Phys. Rev. D* **53** 2658
- [14] Dine M, Nelson A E and Shirman Y 1995 *Phys. Rev. D* **51** 1362
- [15] Fox H (for the CDF and D0 Collaborations), *in these proceedings*
- [16] Aaltonen T *et al.* (CDF collaboration) 200X, accepted by *Phys. Rev. Lett.*
- [17] Fairbairn M, Kraan A C, Milstead D A, Sjöstrand T, Skands P, Sloan T 2007 *Phys. Rept.* **438** 1
- [18] Arkani-Hamed N and Dimopoulos S 2005, *JHEP* **06** 073
- [19] Giudice G and Rattazzi R 1999 *Phys. Rept.* **322** 419
- [20] Goncharov M (for the CDF and D0 collaboration), *in these proceedings*
- [21] Abazov V M (D0 Collaboration) 2007 *Phys. Rev. Lett.* **99** 131801
- [22] Aaltonen T *et al.* (CDF Collaboration) 2007 *Phys. Rev. Lett.* **99** 1217801
- [23] Balasz C, Dias J L, He H J, Tait T and Yuan C P 1999 *Phys. Rev. D* **59** 055016
- [24] Carena M, Mrenna S and Wagner C 1999 *Phys. Rev. D* **60** 075010
- [25] Carena M, Mrenna S and Wagner C 200 *Phys. Rev. D* **63** 055008
- [26] Balasz C, Carena M and Wagner C 2004 *Phys. Rev. D* **70** 015007
- [27] Jonsson P 2007 *in these proceedings*
- [28] Savoy-Navarro A 2007 *in these proceedings*
- [29] Haba J 2007 *in these proceedings*
- [30] Miyazaki Y 2007 *in these proceedings*
- [31] Wilson F 2007 *in these proceedings*
- [32] Spadaro T 2007 *in these proceedings* KLOE
- [33] Fandechi R 2007 *in these proceedings*
- [34] Arkani-Hamed N, Dimopoulos S and Dvali G 1998 *Phys. Lett B* **429** 263.
- [35] Randall L and Sundrum R 1999, *Phys. Rev. Lett.* **83** 3370.
- [36] Aaltonen T *et al.* (CDF Collaboration) 2007 *submitted to Phys. Rev. Lett.* arXiv:0707.2524
- [37] Abazov V M *et al.* (D0 collaboration) 2007 *submitted to Phys. Rev. Lett.* arXiv:0710.3946